MAXIM
Preliminary Design

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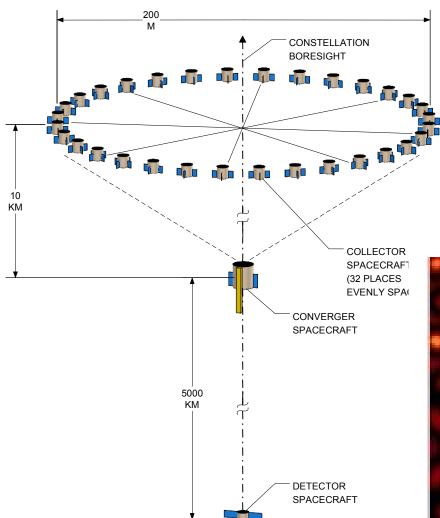

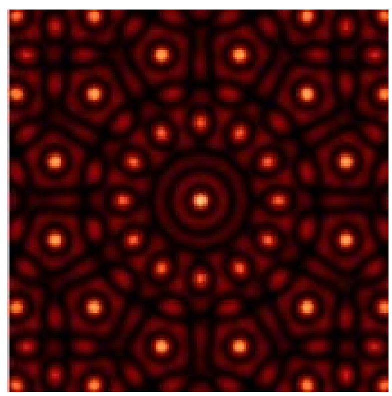

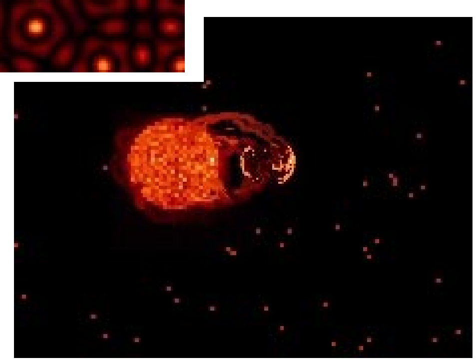

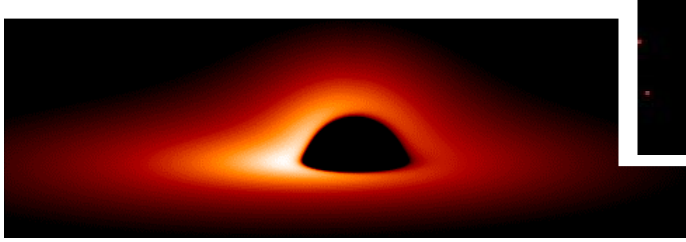

OVERVIEW

The Micro-Arcsecond X-ray Imaging Mission (MAXIM) is the conceived to be an x-ray observatory with sub-microarcsecond resolution, sufficient to resolve the event horizons in AGN's and study the behavior of matter in extreme gravitational limit. With additional study it should be possible to fully demonstrate a reliable technical path to the launch of an exciting new class of scientific mission. We show that angular resolution a million to a billion times higher than that of the Hubble Space Telescope is within our technical grasp.

The x-ray band of the spectrum is the natural band for ultra-high resolution imaging. The sources have very high surface brightness, the features are often very fine, and the short wavelengths allow high resolution in relatively small instruments. The extraordinary improvement in resolution will enable new probes of extreme environments like the warped space-time regions above the event horizons of black holes.

In this report we present some instrument design concepts for the observatory. We tabulate and explain the mission requirements and the instrument tolerances that emerge therefrom. A strawman mission concept is proposed.

We review all the component technologies that are needed to put together a full mission. From these we identify which are the key technologies that need attention before a mission can, with confidence, be built.

One major feature of the mission concept is that the resolution can be improved by flying the primary mirrors farther apart to create a longer baseline. As the distance between the mirrors rises, the positional tolerances do not tighten, but remain the same. Thus there is no limit on resolution as long as the system can function across the larger distance. We have studied the limits on resolution and feel that system can function down to a few nano-arcseconds and possibly below.

I. Goal of the Study

As part of its mission to Explore the Universe, NASA has always maintained an aggressive program in space astronomy. X-ray interferometry will fit naturally into this program. The huge advances in resolution will provide unparalleled views of deep space, making objects appear a million times closer.

X-ray interferometry can be so powerful that it will:

- resolve the event horizon of a supermassive black hole in an AGN,
- observe a 100km emission knot on the surface of Alpha Centauri,
- image the disk of a star in the Magellanic Clouds,
- map the accretion disk at the center of the Milky Way in detail.
- directly measure the parallax of a star in the Virgo Cluster of galaxies,
- resolve one tenth of a light year at the far extent of the visible universe.

From a programmatic perspective x-ray interferometry is also a good fit. Like all x-ray astronomy, it can only be done from space. However, it provides some challenges to NASA's engineering expertise, including:

- Precision formation flying of multiple spacecraft
- Interferometric pointing control of spacecraft
- Active metrology for high internal spacecraft stability
- Stable drift-away orbital environments
- High precision target acquisition

Luckily, our requirements do not stand alone. All of the above challenges are also being addressed by other missions in NASA's plans. Chief among these are ST-3, LISA, and SIM.

II. Requirements

A. TARGET PROPERTIES

Over the past 10 years the study of black holes has moved from a quest to prove their existence, to detailed studies of their effects on space-time and testing the of physics under extreme conditions. This change in emphasis has been driven by X-ray, optical, and radio breakthrough observations. These have established that stellar mass black holes in our galaxy and supermassive black holes (millions to billions times the mass of our Sun) at the

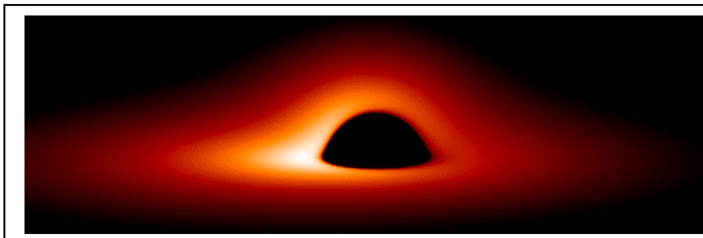

Figure 2.1: Simulation of the distribution of x-ray emission from the inner accretion disk of a black hole. The warped shape is due to the orbits of the photons over the top of the hole. The dark spot is the plunging region where Keplerian orbits fail.

nucleus of galaxies are relatively commonplace.

An entirely complementary and more powerful method of examining these black hole laboratories would be to take an actual picture. The ultra-high resolutions required (1µas or better) have, until now, been viewed as prohibitive, but the realization that X-ray interferometry is feasible puts this holy grail of X-ray astronomy within our technological grasp. Such images would provide the ultimate proof of existence of these most extreme objects. They would allow us to study the exotic physics at work in the immediate vicinity of black holes—the physics of the innermost accretion disk, hard X-ray emitting corona, the formation of relativistic jets, and the "plunging" region in which material undergoes the final spiral through the black hole magnetosphere towards the event horizon. These images would be amongst the most influential scientific images of the new century.

The quest to image a black hole would capture the imagination of scientists and the public alike. While it may seem contradictory to image an object from which light cannot escape, the black hole can be seen in silhouette against the hot material spiraling toward the event horizon. We would directly observe light from the accretion disk bending around the black hole and so see the actual distortion of space-time by the intense ultimate gravitational field. The best candidate black holes to observe are the nearby active nuclei (AGN). For example the AGN in M87 is believed to harbor a 100 million solar mass black hole at a distance of order 1 million parsecs. Depending on whether the black hole is rotating or not, an angular scale of 3 to 6 micro arc-seconds is required to resolve the event horizon of the supermassive black hole in M87.

It is worth noting that the capabilities of MAXIM would be such a huge leap forward, that it would have an enormous impact in all areas of astronomy, not only the study of black holes. We could capture detailed images of the coronae of other stars, map the plasma activity in newly forming stellar systems, follow the motions of material ejected in supernova explosions, and watch material cooling at the center of clusters of galaxies.

A. BASELINE

The resolution of the interferometer scales with the baseline between the extreme ends of the interferometer. The resolution is given by:

$$\theta = \frac{\lambda}{2B}$$ where B is the baseline.

In this table we show some characteristic targets and their angular sizes. We can think of nothing smaller than a neutron star that is likely to be of particular

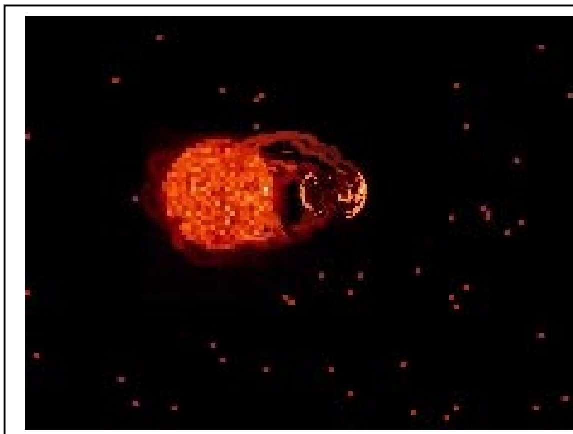

Figure 2.2: Artist's conception of the shared corona of a close binary star as imaged by an interferometer in the x-ray.

interest, so a baseline of 10,000km appears to be about the maximum we should consider.

Table 2-1: Targets and their Characteristic Sizes

Target	Angular Size (radians)	Baseline at 10Å
Sun at 1pc	$5x10^{-8}$	1cm
AGN Accretion Disk	$5x10^{-10}$	1m
AGN Event Horizon	$5x10^{-12}$	100m
Binary Accretion Disk	$5x10^{-14}$	10km
Neutron Star	$5x10^{-16}$	1000km

Baselines of up to a meter can be handled in a single spacecraft. Above a few tens of meters we need to place the optics on separate spacecraft. But, to truly achieve the potential of x-ray interferometry, we should use the separate spacecraft, allowing us to fly from as close as 50m baselines to as far apart as 1000km. Our minimum acceptable is 100m, and the maximum needed is 1000km.

B. COLLECTING AREA

The collecting area required of the observatory can be estimated on very simple grounds. Choosing an exact size and bandpass will come later, so we need only be approximate for now.

A mission with just one square centimeter would be able to get a few high quality images by spending days per target. We risk the target itself changing during that time, so we need more area. $10cm^2$ is better. The Einstein observatory was able to collect a substantial number of quality images with just $5cm^2$, so this represents an absolute minimum. However, we would not be able to perform serious work on many classes of target. At $100cm^2$, we can observe a fair number of targets in every category. However, for most targets there will be a dearth of photons. At $1000cm^2$ we would match the collecting area of Chandra, and be able to acquire high resolution images on many objects. At $10{,}000cm^2$ we would not only have enough area to fill in the pixels on high resolution images, but enough signal to separate into energy resolved images and time-resolved images. This would allow us to watch and analyze real-time events like flares on stars and redshifting matter falling into black holes.

It is clear that we should place $10{,}000cm^2$ as our goal, and recognize that excellent observatories could be realized with substantially lower area.

C. IMAGE CONTRAST

Image contrast is not a major driver of the instrument design. For the most part, the quality of the results does not depend on being able to observe faint features close to bright ones. Achieving 10:1 ratios between signal and noise requires only 50% control of the intensity of the mixed beams. To achieve 1%, still requires only 20% control. This is easy to achieve and maintain, and perfectly acceptable for the images needed.

D. FIELD OF VIEW

The field of view requirement is again related to desired image quality. A 10x10 image is hardly better than a tic-tac-toe board and is unacceptable. A 100x100 image would be just fine. At 1000x1000 we approach the image quality of HST. Thus, it is clear we require a field of view of 100x100 resolution elements, with a goal of pushing higher, to 1000x1000.

III. Tolerance Analysis

The tolerance analysis is surprisingly simple. In figure 3.18 we show the geometry of a wavefront on a flat mirror at grazing incidence. The idea is to keep the paths from the source at infinity to the detector the same to within a quarter of a wavelength along the emerging beam.

In the figure we derive the pathlength difference and set a tolerance limit on the motion of the mirror surface. The formulae reflect the same 1/theta forgiveness that we find in conventional grazing optics. In particular, the separation of the two mirrors must be held to $\lambda/8\sin\theta$ if the fringe position is to be held to one part in 4. From this formula emerge most of the other tolerances in the system as well.

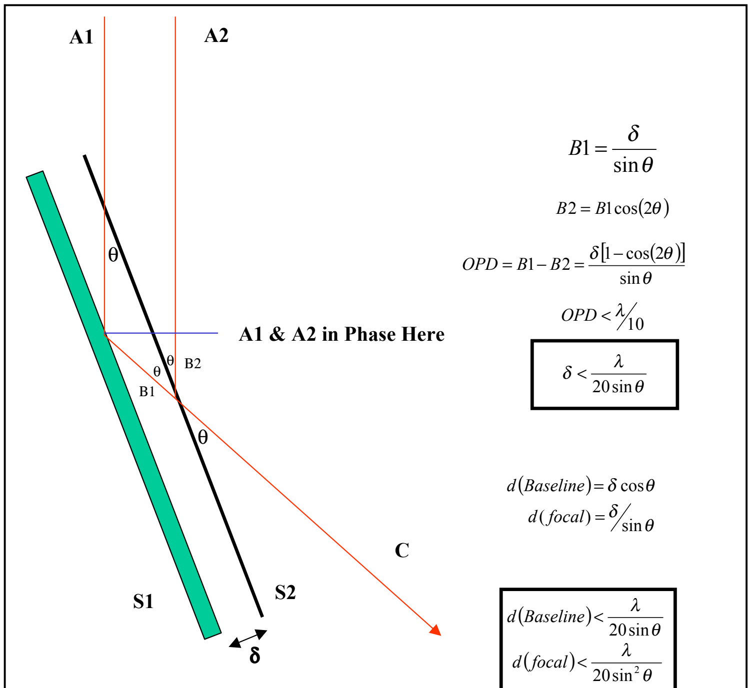

Figure 3.18: Geometry of a surface or positioning error in a grazing incidence optic. The errors are

The quality of the mirror is similarly related to the formula, as no part of the surface can exceed $\lambda/20\sin\theta$ deviation from the nominal. At 1nm and 2 degree graze this amounts to 3.6nm. This corresponds to what would be called a $\lambda/175$ mirror – very high quality but also well within the state-of-the-art. Flats and spheres can be made to this tolerance. Even aspheres can be made to this tolerance. However, the extreme aspheres of Wolter telescopes cannot, at present, be made this well. This is another reason that the use of flat mirrors appears attractive.

Table 3-1. X-ray Interferometer Tolerances

Resolution Arcseconds	1	0.1	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Mirror Length (m)	0.1	0.1	0.3	3	3	3	3	3
Position Stability (nm)	200	20	2	2	2	2	2	2
Angular Stability (arcsec)	50	10	2	0.3	0.1	0.01	10^{-3}	10^{-4}
Figure	$\lambda/5$	$\lambda/20$	$\lambda/50$	$\lambda/100$	$\lambda/100$	$\lambda/100$	$\lambda/100$	$\lambda/100$
Polish (Å rms)	50	30	20	20	20	20	20	20
Baseline (m)					1	10	100	1000
Angular Knowledge (as)	0.3	0.03	3×10^{-3}	3×10^{-4}	3×10^{-5}	3×10^{-6}	3×10^{-7}	3×10^{-8}
Position Knowledge (nm)					20	20	20	20
$E/\Delta E$ Detector					10	20	100	100

In Table 3-1 we show the specifications needed to build X-ray interferometers that function down to 10^{-7} arcseconds.

IV. Mission Concept

To make clear how all of the mission components come together, we present a mission concept. It is not meant to be in any way optimal, but instead to demonstrate how the problems of the mission can be solved in a coherent fashion.

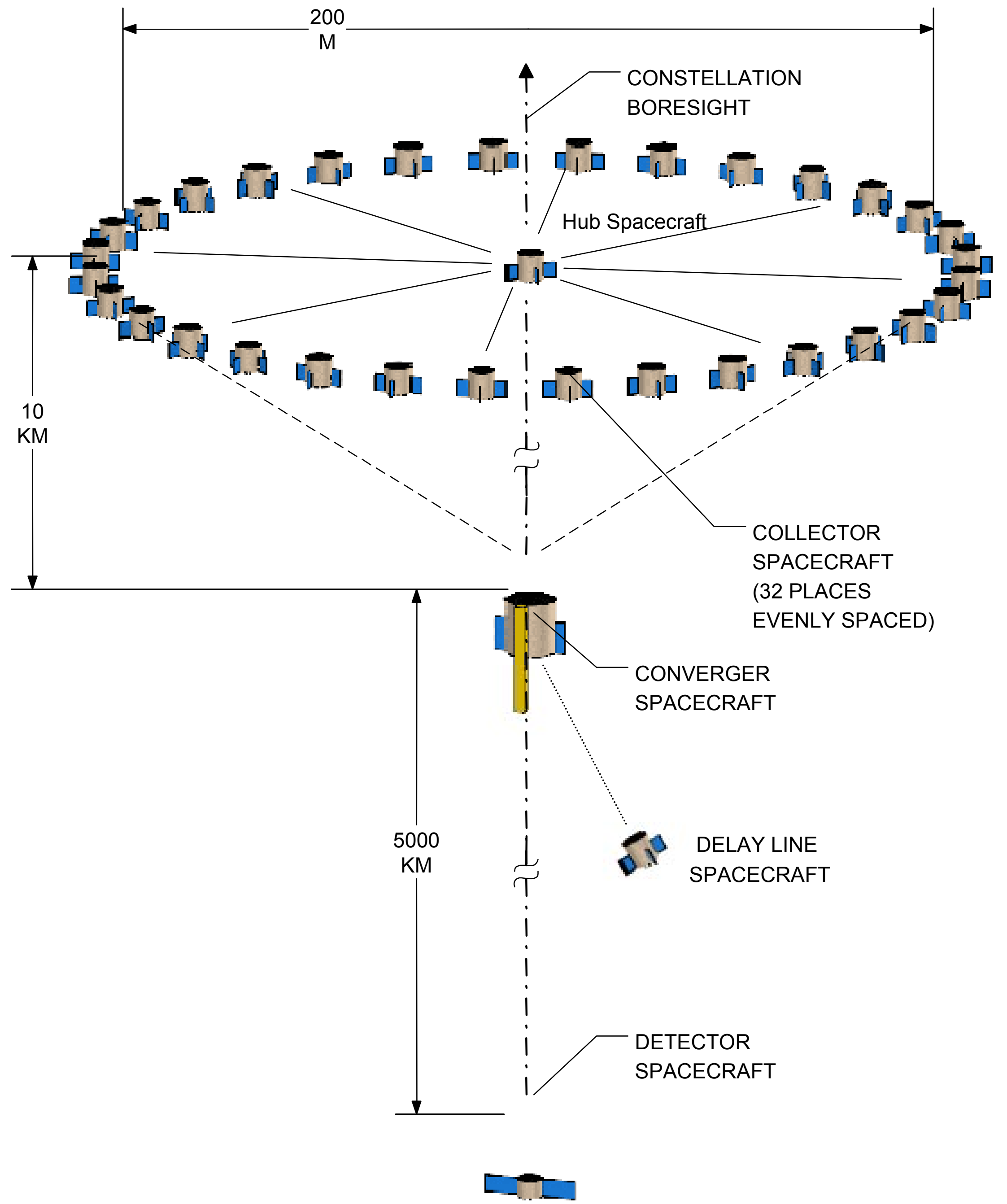

Figure 4.1: Schematic of the overall layout of the mission. The converger craft in the middle collects the radiation from 32 collector spacecraft. The hub craft, together with the delay line craft keep the system pointed to high precision.

A. OPTICAL ARRANGEMENT

The optical layout requirements drive the overall size and configuration for the mission. We have used as a baseline an array of 32 phased flat mirrors as described in section III.C. This allows us to enjoy a wide field of view and good signal to noise at the focal plane.

As we wish to observe event horizons and other extremely small targets, the baseline must be in excess of 100m. At these baselines it is impractical to build stable structures, so we need to place the individual flat mirrors on separate spacecraft, and hold their positions to optical tolerance. Thus, we envision an assembly of spacecraft as in Figure 4.1. Each of the collector craft in the assembly contains a flat mirror that is directing light from the target onto the converger. Within the converger craft is an array of flats that redirects the beam toward the detector spacecraft.

Since the system uses flat mirrors, there is no focal constraint between the mirrors in the collector spacecraft and the mirrors in the converger. Thus, flying the collectors out onto a larger circle, farther in front of the converger, can increase the baseline. The converger and detector do not change. The resolution rises.

B. DETECTOR

The choice of detector for the mission is limited. We need good energy sensitivity if we are to be able to detect fringes more than a few away from the central null. This requires that the detector be either a CCD or an imaging Quantum Calorimeter (QC).

The CCD has several advantages. First, it is a well established technology with a good track record in space. Second, it is a simple technology, not requiring fancy cryogenics. On the other hand, the energy resolution is marginal to the task at hand. For example, at 1kev, a CCD can generate $E/\delta E$ of about 20. We cannot allow the interference lines to be blurred by more than one quarter, or the image suffers badly. This implies that the maximum number of fringes across the field of view should be $E/2\delta E$ or 10 for the CCD and there will be at most 20 resolution elements across the full field of view. This is significantly less than we wish to achieve. Use of the phased array of flats can mitigate this by forcing the fringes further apart.

The QC, however, can have resolution as high as $E/\delta E$ of 1000. This allows the field of view to be as high as 1000x1000 without even requiring the effects of a phased array. At 1000x1000, the image is so large that most sources are insufficiently bright to provide adequate signal across such a large format.

C. ASPECT

Controlling the pointing of the array is without doubt, the most subtle aspect of the formation array design. We propose the following solution, but suspect that more efficient approaches exist.

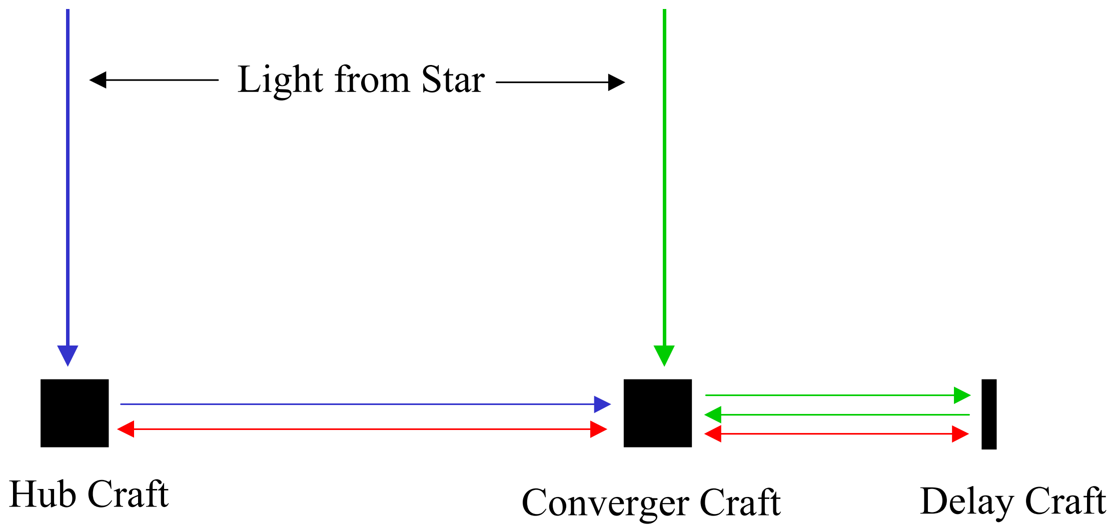

Figure 4.2: The hub craft and the converger craft together function as a stellar interferometer to gather the information needed for ultra-high precision stability pointing. The delay craft is needed to equalize the path lengths for the two optical paths.

We start by placing a spacecraft at the hub of the 32 collector craft. It will become the reference point which the collector craft will use to maintain position. The hub position that the craft must find and maintain is on the line that stretches from the center of the converger mirrors to the target in the sky.

Two stars, each close to perpendicular to the line of sight to the target, and nearly perpendicular to each other are chosen. In Figure 4.2 we show the wavefront approaching the hub craft and the converger craft which, together, form an interferometer. The light impinging on the hub craft is reflected through 90 degrees and sent to the converger. Thus, by the time it reaches the converger, it has traveled farther than the (green) beam that reaches the converger. The light that strikes the converger is then sent to a delay line spacecraft that equalizes the path lengths and allows a null interferometer to be built in the converger. The distance between the converger and the hub, and between the converger and the delay craft must be monitored by laser beam and stabilized with formation flying. Then, if the craft fall off the target line, a shift in the null will be recorded.

Unfortunately, both pitch and yaw need maintenance. This requires that the process be simultaneously maintained on two stars. Since the stars cannot be perfectly placed, the delay line length will have to be different. Thus, it may be necessary to have two delay line craft. The good news is that the delay line craft can be very similar in size and performance to the collector craft, so the addition of two more craft to the fleet does constitute a major increase in mission complexity.

D. FORMATION FLYING

Once the hub craft is firmly fixed along the line of sight to the target, it may be used to maintain the position and separation of the collector craft. Each collector craft then directly monitors and maintains its distance to the hub. This is the most sensitive

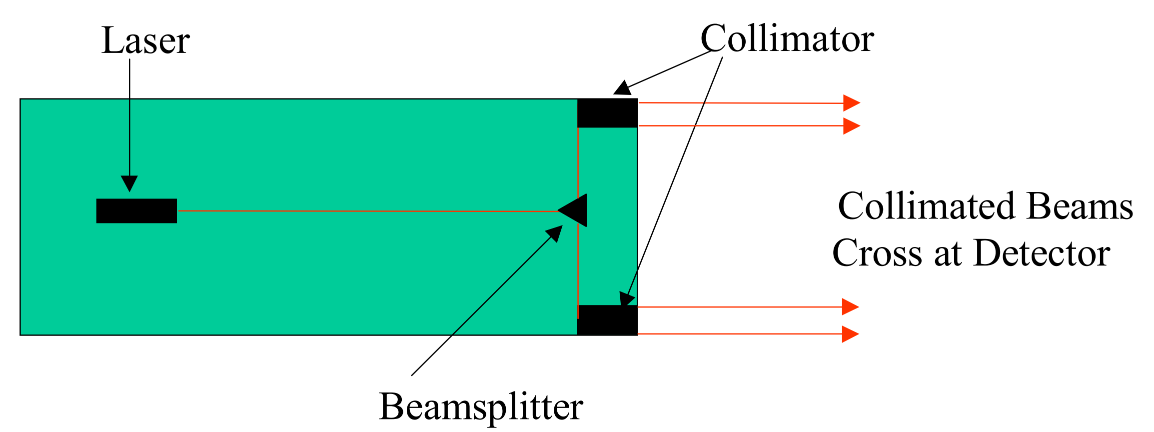

Figure 4.3: The light from the laser is split and sent through parallel collimators.

direction, requiring stability of about 1nm. Simultaneously, each craft must maintain its distance from the converger craft, although at a looser tolerance. The separation between the craft must also be maintained, but this also is more relaxed.

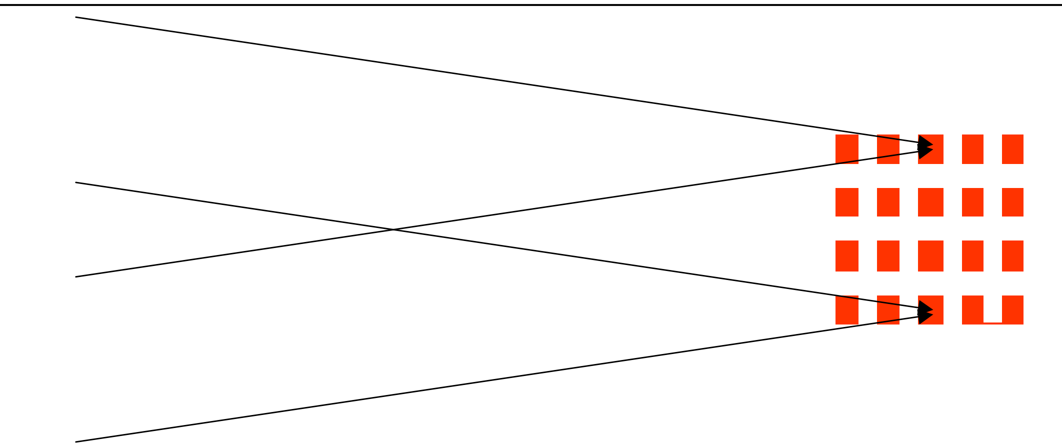
Figure 4.4: When the beams from the four collimators cross, the create a fringe pattern that can be used to provide the necessary information for holding the detector craft in the correct position.

The position of the detector is a bit tricky too. Its distance from the converger, though large, is not a sensitive parameter. We can handle this by creating an interference pattern from the back of the converger craft. We show in Figure 4.3 a laser beam on the converger craft that is split and then passed through four collimators. When the nearly parallel beams cross at the distance detector craft, as in Figure 4.4, they create a fixed interferometric pattern that the detector craft can use to slave its position to the optic axis of the converger.

E. SPACECRAFT

On the whole, the individual craft are not particularly fancy. They carry retro-reflectors, stabilizing gyros and lasers, but their overall structures, power requirements and data requirements are modest. The aspects of the spacecraft that are challenging are discussed in the next section.

V. Technical Challenges

A. FORMATION FLYING

To minimize disturbances, the constellation of spacecraft operates in a heliocentric driftaway orbit with a semimajor axis of 1 Au and an ecliptic inclination of zero. To minimize thermal stresses on the S/C, the constellation boresight is always oriented at right angles to the sunline, although it is free to rotate 360 degrees around it.

In operation, the Converger, by far the most massive of the S/C operates in the orbit plane at all times to minimize the constellation's propellant consumption. Depending on the orientation of the constellation boresight about the sunline, the collector S/C position will be in a range from 0 to 10 km from the ecliptic plane. The lightest S/C, the detector, will operate in a range of from 0 to 5000 km from the plane.

To keep the S/C in their correct positions to this level of accuracy for all possible constellation boresight orientations, they must be continuously stationkept against forces exerted by solar radiation pressure and solar gravity.

Solar radiation exerts a constant pressure on the order of 5 to 9 E-6 N/M2 at 1 Au on each S/C in the constellation. The exact value will depend on the reflectance of the S/C. the pressure will be constant, as each S/C's attitude with resect to the sun is constant for all allowed boresight orientations. Solar radiation pressure disturbances will be minimized by equalizing the "ballistic Coefficient" or area mass loading of each of the constellation's S/C elements, using light weight solar sails if necessary. This approach will keep the magnitude of solar disturbances small compared to the solar gravitational forces, allowing the stationkeeping system to be designed to compensate for solar gravity effects alone.

Solar gravity exerts forces on the Collector and Detector S/C as they operate in "non-Keplarian" orbits. The more massive Converger S/C is force free, as it alone is in a true Keplarian orbit at 1 Au radius and always in the ecliptic plane.

Gravitational forces are maximum for the detector S/C when the constellation boresight is normal to the ecliptic plane, elevating (or depressing) the S/C by 5000 km above or below the plane. This imparts a constant acceleration on the order of 2 E-7 m/s2 in a direction perpendicular to the ecliptic plane (PEP) to the detector S/C. If uncompensated; this acceleration would relocate the S/C by about 750 m/day. For the same constellation orientation, the Collector S/C, operated on by acceleration forces two orders of magnitude lower, would be displaced by about 1.5 m/day.

For a Nominal 1000 kg Detector S/C, compensating this gravitational acceleration would require a continuous force of about 198 μN. The force required to provide an equivalent force compensation for the collector S/C is on the order of 1 to 2 μN. Nominally, these forces act along the constellation boresight. However, the need also exists to compensate for second order forces (such as minor differences in ballistic coefficient, or the gravity of earth or Jupiter) which even though lower in magnitude by two or three orders of magnitude are effectively omnidirectional, and over many days or weeks can induce many meters of displacement.

The full range of these requirements could be met for the collector S/C by providing for a continuous force on the S/C of 0 to 0.5 μN in each or 3 axes. The total worst-case impulse delivered to the S/C using this approach is about 12.6 N-s per year, or 126 N-s per axis over 10 years.

The equivalent pulse plasma thruster (PPT) complement for the detector S/C would require the same force and total impulse level for the two axes transverse to the constellation boresight. Along the boresight axis, however, up to 100 μN thrust and 3154 N-s of impulse per year will be required, for a total of 31,540 N-s for 10 years.

2) Notional Stationkeeping Approach: While many approaches can meet these requirements, a notional approach using flight proven PPTs can meet the requirements described with minimum system impact while providing a minimum ten year mission life with margin.

Each of the collector S/C will be equipped with 6 to 8 PPT's each of which thrusts through or along an axis parallel to one that passes though the S/C CG. The thrusters are located to provide 3-axis translation of the vehicle without inducing moments.

All three of the Collector S/C axes, and the transverse axes of the detector S/C, are equipped with 17 μN PPT units of the type used on the DOD LES-6 mission. These thrusters operate at an Isp of 300 s, operate on 6 W of power, and have a total impulse capability of 320N-s, providing a lifetime of > 10 years with over 100 % margin when compared to the 126 N-s requirement.

Thrusters for the boresight axis of the detector S/C will be larger units or the type used for the DOD LES 8/9 mission, which weigh 6.6 kg each, and feature a thrust level of 300 μN and an Isp of 1000 s. These units require 25 W, and provide a total impulse of 9940 N-s each. Four of these units will provide a total of 33,600 N-s, yielding a margin of 26% over the 10-year requirement. The thrusters would be used in pairs, with two burning at a time to limit power consumption to 50W. Alternatively, new PPT thrusters with a higher total impulse capability could be developed.

B. ASPECT CONTROL

1) Aspect Control Requirements: Between observations, the MAXIM constellation must slew between targets. The following requirements and groundrules were adapted to guide definition of the slew approach:

- The Converger S/C is equipped with order 10m pitch and yaw interferometers with 4 microarcsec resolution to lay the constellation boresight
- Collector and Detector S/C pointing control uses Converger attitude knowledge plus metrology
- All S/C equipped with 20 arcsec class ADCS for setup of metrology chain after slew

- All S/C equipped with 5 m class autonav for setup of metrology chain
- Constellation boresight axis always perpendicular to sunline
- All boresight slew maneuvers are around sunline
- Constellation Boresight re-orientation rate 5 deg/day max
- Constellation roll attitude (about boresight axis) controlled to allow for collector metrology sun avoidance of 10 deg max
- Constellation Roll attitude maneuver for collector metrology sun avoidance on 5 day centers
- Aspect re-orientation maneuvers are point-to point
- No X-ray interferometry during re-orientation maneuvers
- 6 hour "constellation re-build" after each aspect maneuver to achieve full metrology accuracy

2) Notional Aspect Control Approach: Figure 5.1 shows a schematic view of a typical constellation slew maneuver. The entire constellation pivots about the CG of the massive Converger S/C, forcing the ring of collector S/C and the single Detector S/C to translate to their new positions. All translations are "point-to-point" along the shortest path to minimize propellant consumption. To further minimize propellant usage, all translations use a boost-coast-deboost trajectory, where the S/C is accelerated to a fixed velocity chosen to achieve the required translation in the designated time, coasts for the bulk of the translation period, and then decelerates to come to rest in its new position.

Inspection of the figure shows that the translation required by the detector S/C is four orders of magnitude greater than that of the Collector S/C (436 km compared to 9m) because of the Detector S/C's 5000 kg "lever arm". The required translation for the Collector S/C can easily be handled by the PPT thrusters used for stationkeeping, at a propellant consumption per S/C of about 0.03 g for a five-degree re-orientation.

Accordingly, the challenge in aspect control becomes that of translating the detector S/C 436 km in one day (for a 5-degree boresight slew). In our notional approach, this is accomplished by thrust from a 0.2 N hydrazine arcjet, of the type currently used for GEO Comsat N-S stationkeeping. This unit features an Isp of 600s, requires about 2 kW of electrical power, and has a dry mass of less than 22 kg for two thrusters.

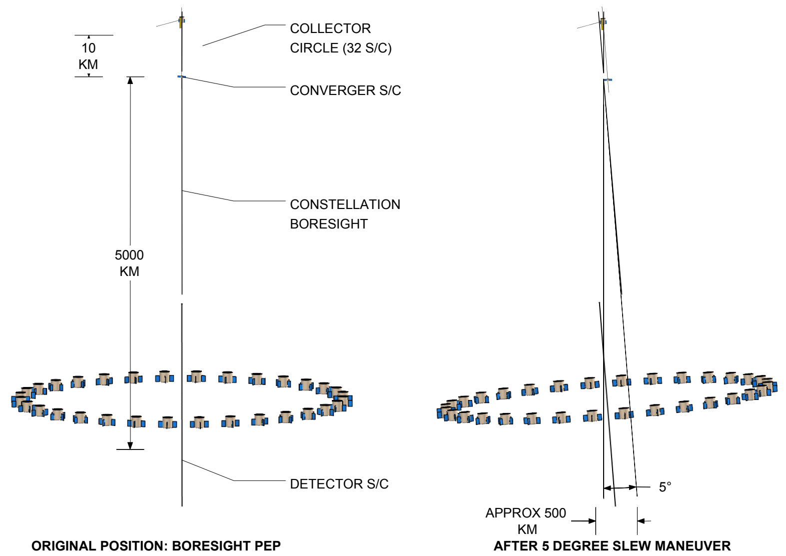

Figure 5.1: Five degree slew maneuver.

In operation, when a boresight slew is required, the arcjet is fired for about three and a half hours to accelerate the collector S/C to a velocity of 5 m/s (18 km/hr). This is sufficient to cover the required 436 km in one day. As the final position is approached, a second arcjet fires for 3.5 hr to bring the S/C to rest. The low rate of acceleration has been chosen to minimize the thrust level, and electrical power demand, of the arcjet. The arcjet was chosen as opposed to hydrazine thrusters because of its 600-s specific impulse, which consumes only 900 g of hydrazine for the 5-degree re-orientation. A hydrazine monopropellant approach would use almost 3 kg of hydrazine for the same translation.

3) Aspect Control Limits: Given the baseline constellation separation of 5000 km, then for small boresight slew angles, and a 1 day slew duration, the propellant burn per slew is proportional to the slew angle, yielding a propellant consumption of about 180 g per degree for the baseline arcjet thrusters.

If we assume an optimal observational strategy for the constellation which limits slews to an average of 1 degree/day, annual propellant consumption will be 66kg, or 660 kg for 10 years. This is well beyond the lifetime propellant thruput limit of existing arcjets (about 180 kg). This is a definite limit.

Extension of the constellation converger to detector distance will increase the propellant consumption in direct proportion to the increase in distance. Even for the increased efficiency propulsion systems described below, this will probably limit practical converger to detector distance increases to a factor of two at most.

A number of alternative, higher specific impulse propulsion approaches exist, among them ion, magneto plasma dynamic, and stationary plasma thrusters. Each potentially offers a factor of four or better reduction in propellant consumption, at the price of an equivalent increase in power draw. A detailed trade study will be required to define

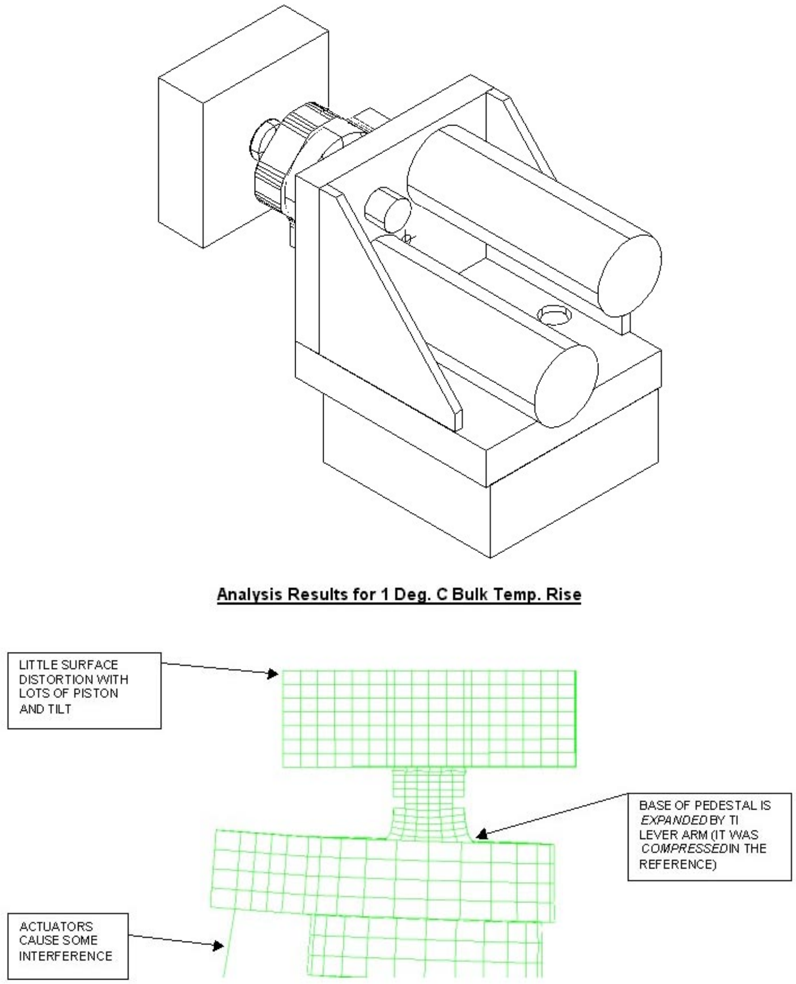

Figure 5.2: Finite element analysis of a low stress mount for mirrors has been started.

which of these options provides the best combination of cost and performance for the operational MAXIM constellation.

C. MIRRORS, MOUNTS, ALIGNMENT AND THERMAL

The interferometer's active area requirement and proposed instrument configuration drive the mirror geometry to a long narrow shape. This represents a challenging mirror shape to mount even with relatively loose surface figure requirements. Current tolerance studies indicate each mirror's surface accuracy will be required to meet $\lambda/100$ rms surface figure with less than 5Å surface roughness. Such an accurate surface figure requirement makes many subtle errors significant in estimating the total wavefront error. An acceptable mounted mirror's $\lambda/100$ surface must include errors due to alignment, thermal gradient, jitter, stability, assembly, manufacturing, test, 1g release, temperature

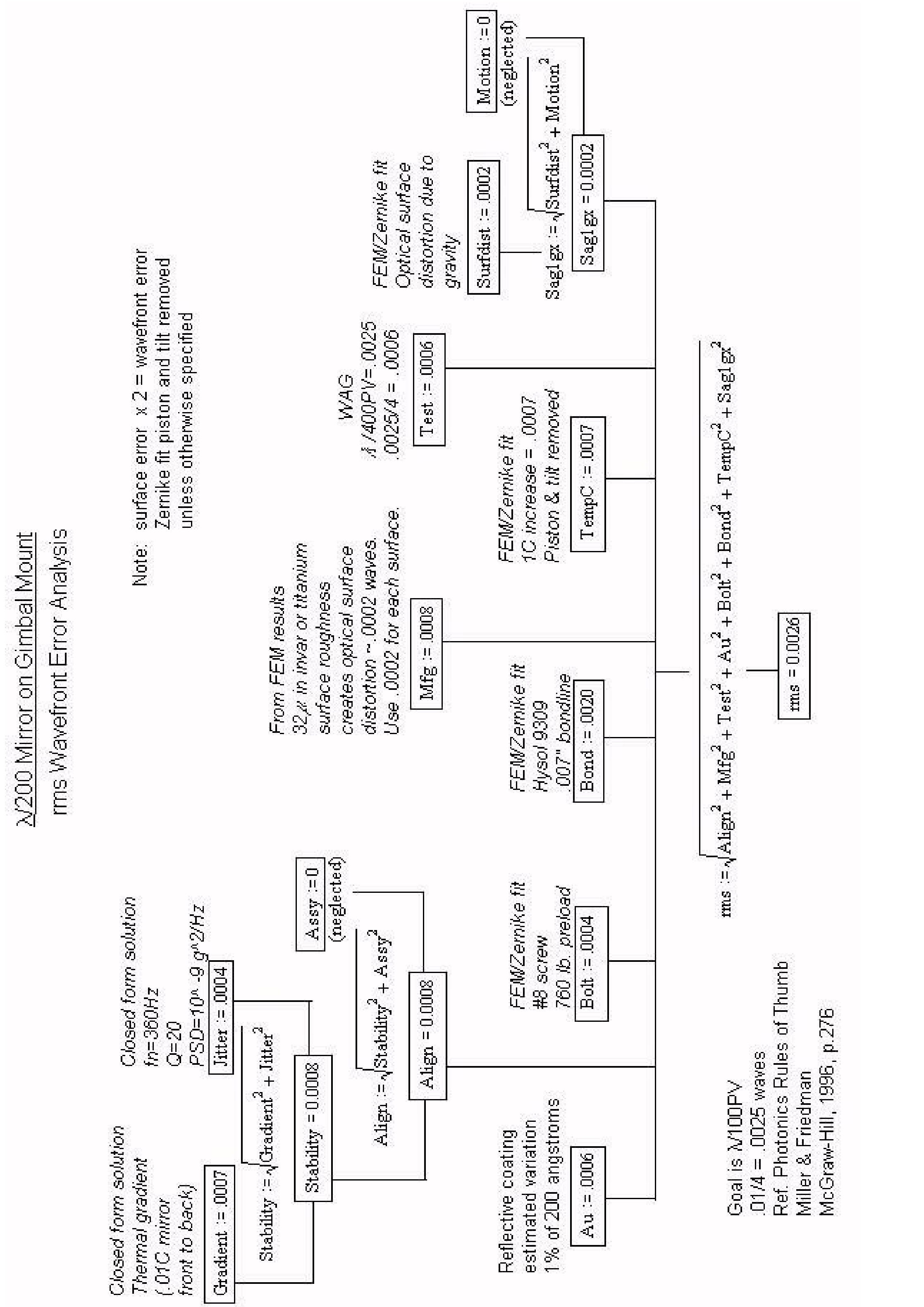

Figure 5.3: Mounting of high quality mirror mount is a necessary step to launching the mission. Analysis is already underway.

coating thickness variation. We can guess which errors will have the greatest effect on a mirror of this size and shape, however we have chosen to solve this problem in stages. Investigating a smaller mirror mount with similar requirements has given us the ability to quantify the errors and environmental effects most likely to become drivers that will require technology development. This approach allows us to break down the problem into smaller parts to identify areas that require technological advancement uncoupled from the known challenge involved with the mirror's size and shape. Additionally, we have completed the analysis for a smaller system that can be built and tested in a scaled down model of the interferometer. Such tests will be imperative to identifying real-time alignment, thermal, imaging, vibration/jitter, and other unknown subtleties requiring early attention that may not be apparent through analyses.

The analysis of a smaller mirror mount with similar requirements and analytical results indicate a $\lambda/400$ rms ($\lambda/100$ PV) surface figure is reasonably attainable for a 50mm square mirror made of fused silica. Wavefront error analysis based on those analytical results suggest the most challenging factors include: thermal gradient, and piston and tilt error associated with a bulk temperature increase (optical surface distortion is reasonable). The estimated allowable thermal gradient between the front and back of a mirror may be less than 0.01°C. The piston and tilt error of the mirror associated with a change in the stabilized temperature will probably drive the allowable time length of an observation. The mirror positions will need to be corrected between observations to

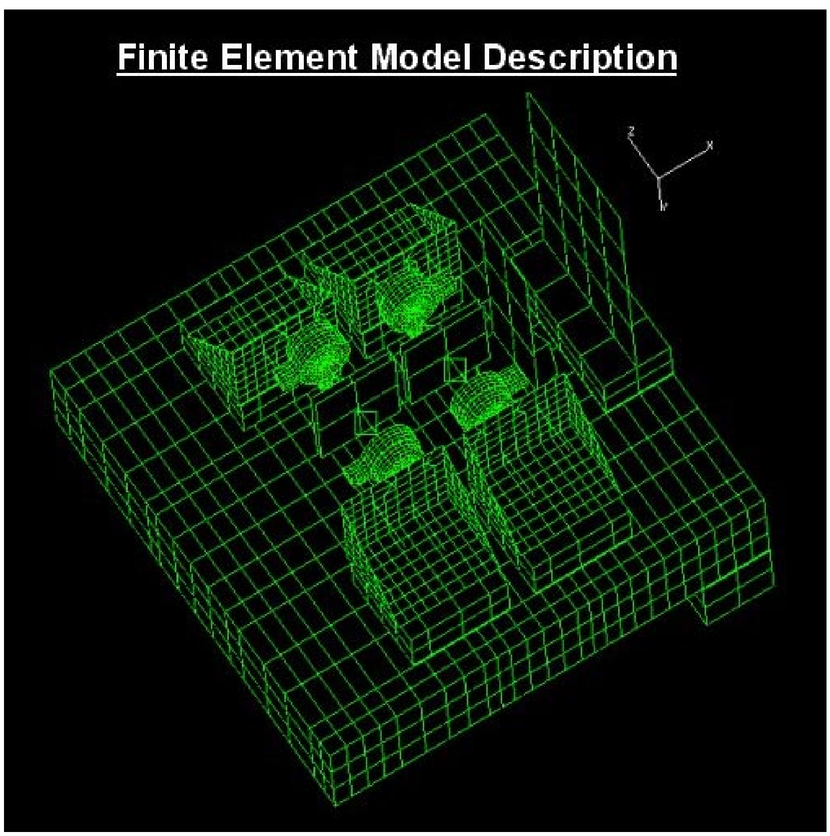

Figure 5.4: Assembly of mirrors in arrays is also being studied.

maintain equal pathlengths. The mirror substrate thermal gradient will be difficult to maintain because heat emitted by motors used to manipulate the mirror position will make temperature difficult to stabilize. Materials with improved thermal properties could make this problem more easily contained in the future. Motors capable of high-resolution, stability, and position knowledge that emit very little heat would also help.

The long narrow mirrors will have the same thermal challenges at a much greater magnitude. A challenging parameter for a small mirror certainly indicates an imperative need for technological advancement to support similar requirements in a much larger mirror. Other factors we expect to be difficult are gravity release, stability due to jitter (a function of the mirror's fundamental frequency and mode shape), and the ability to test the mounted mirror's surface figure. The mirror size and high surface accuracy require a test apparatus beyond standard laser interferogram capability.

Gravity release and jitter stability of a mounted mirror may require the development of a stiffer material with lower mass, good stability over time, and of course a lower thermal coefficient of expansion. Current materials used for high quality optics have good thermal and mechanical stability, however, these materials also tend to be brittle, prone to fracture, and mass can be prohibitive for large optics. Traditional optic fabrication methods are well suited for symmetrical optics made of traditional materials. We plan to analyze the mirror mount configurations employing existing optical materials. Traditional materials such as Zerudor, ULE, and fused silica may be viable candidates with the advent of thermal technological advancement. New methods of fabrication and polishing may also be required to support a design using traditional materials. Two possible avenues are active self-aligning optics and segmented mirror sections (up to seven meters long) making up one long narrow mirror. New hybrid materials may be necessary to achieve the next level of accuracy and size in space-borne optics.

Active alignment of the optics on-orbit will be critical to maintaining such ambitious resolving power. Our studies using a single channel instrument consisting of four small mirrors have uncovered alignment issues that will apply to each channel of the instrument. Every mirror in the interferometer will require on-orbit motion in three degrees of freedom (tip, tilt, and piston). Current tolerance studies indicate optic alignment in the remaining three degrees of freedom may withstand launch. Attaining equal pathlengths in each channel will require tilt and piston control of each mirror at an estimated 10 nanometer resolution and knowledge. Equalizing pathlengths in numerous channels simultaneously while providing positional stability over the length of an observation may certainly be considered challenging. Developing continuous on-orbit automated sensing and correction to maintain equal pathlengths in each channel of the interferometer simultaneously could eliminate or greatly reduce these effects. The advent of this capability at the nanometer level would provide incredible imaging capability.

Thermal stability requirements will be a function of the length of time during which each channel's pathlengths may not be optimized. This time constraint may lend itself to the time length of an observation. Continuous automated sensing and pathlength correction could loosen some of these thermal requirements making longer observation sessions a reality. Investigating this avenue as part of the system analysis would be beneficial. A clever mirror mount may minimize wavefront error due to thermal changes, but still cause tip, tilt and piston motions that will far exceed allowable tolerances. Once again this thermal issue may be mitigated with the advent of automated alignment corrections. The thermal challenges are significant, but appear to be integrally tied with mirror, mount, and alignment solutions.

D. CALIBRATION

It may not be possible to fully calibrate the instrument on the ground. The longest vacuum tank we have available is the XRCF at MSFC, which is 500m. Resolution of one micro-arcsecond at that distance represents a size scale of 2.5nm. We cannot currently even create mask features this fine. We may have to check components, and then perform an in-orbit checkout.

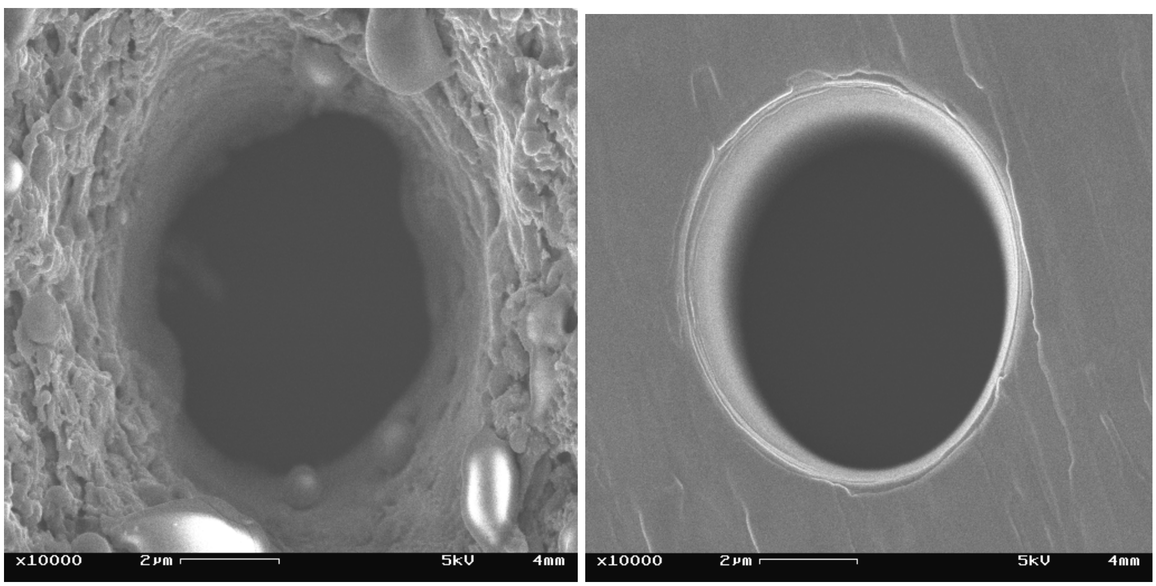

Figure 5.5: To the left, a 5 micron hole was drilled in moly sheet using a laser. To the right focussed ion beam was used. It is clear that the focussed ion beam has excellent potential for the creation of very fine calibration targets.

For the development and testing phase of the mission a critical task is to fabricate high-quality target apertures designed to test the diffraction-limited performance of the optical system. The idea is to use microscope optics to image backlit apertures onto the detector. Target apertures of various shapes are useful, such as holes, slits, cross and wagonwheel patterns, and gratings. In order to fully test the optical system, apertures need to be cut into thin, x-ray opaque foils, and need to have sub-micron feature sizes with sharp edges and corners. Specialized laboratory facilities are required to fabricate targets of this quality. Figure 5.5 shows a recent advance in our ability to make better calibration masks.

E. IMAGE RECONSTRUCTION

Image reconstruction is accomplished in computers on the ground in exactly the fashion that radio interferometers create images. We do not expect any serious problems in this area. Image reconstruction is a standard procedure in the x-ray, most notably used in rotation modulation collimators and in CT scans. However, handling the details will require some software development.

We need to build a software model and start developing and evaluating algorithms that will quickly and effectively create images from the data stream from an x-ray interferometer.

VI. Mission Limitations

In this section we discuss the eventual limitation of the technique in terms of increased resolution. Since the primary mirrors can be flown farther apart to create a longer baseline, the resolution can rise. What limits the practical resolution? We have looked at several important parameters as the size of the primary array grows.

In summary we find that the limit is likely to be aspect information coming from deep space. None of the other effects becomes severe until the baseline of the x-ray interferometer is around 100,000km, with a resolution of 10^{-17} radians. But, most stars have sufficiently low surface brightness in the visible that we either cannot detect them or they become resolved across a baseline of about 100km. Use of non-thermal visible sources or use of an x-ray interferometer may be needed if we wish to push below 10^{-13} radians.

A. STATIONKEEPING

The stationkeeping approach described using existing technology can provide at least a 20 year life for all requirements except along-boresight control for the Detector S/C. The baseline 20 year life could be doubled by simply adding a second set of thrusters to each axis. Accordingly, these requirements are not considered limiting.

Limits are completely dominated by Detector S/C along-boresight control. For equivalent lifetime, total impulse requirements are a linear function of the distance along the boresight; a 10,000 km distance would require twice the total impulse or reduction of the mission lifetime to 5 years. Removing these limits could be accomplished by adding more PPT's, or by using a higher specific impulse propulsion approach such as ion or magneto-plasma-dynamic thrusters. A detailed trade study would be required to determine the optimum approach. In any case, an absolute limit imposed by propellant load would probably be reached at between 50,000 and 100,000 km separation.

B. POSITIONAL INFORMATION

Our positional information must be maintained by monitoring the stability between the primary mirrors and the hub craft. While we have not yet directly worked on the design for such a system, it would probably resemble the separation monitoring system under development for the LISA mission. LISA claims that through use of laser beams fed through a telescope (collimator), that the separation can be monitored to better than a nanometer over a million kilometers.

C. ASPECT INFORMATION

We expect to obtain aspect information by using a Michelson flat at the hub spacecraft to redirect the signal from a stellar object into an interferometer on the converger craft. As the array flies apart, the baseline of this interferometer grows along with the baseline of the x-ray interferometer. Two effects can limit the effectiveness of this aspect interferometer.

First is the diffraction from the Michelson flat. A ten meter optic will cause visible light to diffract one part in $2x10^7$. If the beam is to diffract to less than 100m across, resulting in a factor of 100 loss in signal, then the baseline of the aspect interferometer can be as high as 2 million kilometers. This indicates an x-ray interferometer with a baseline of 200,000km and resolution of 10^{-17} radians.

The other effect is the size of the star being used to provide the reference wavefront. We rapidly start to run out of thermal reference information in the visible portion of the spectrum. We can use main sequence stars at a distance as great as 10,000pc, which have an angular extent of around 10^{-11} radians, which will be resolved across a baseline of 100km. We could use white dwarf stars, but, while they are smaller, they are also dimmer, and we cannot see them a great distances. Similarly, the visible emission of AGN's is too extended. This problem is a direct result of the relative faintness of visible emission from objects. The only hope to solve this problem in the visible is to observe non-thermal objects such as pulsars. The Crab pulsar is detectable in the visible, yet is only a few kilometers across, so might give us the needed information. At a diameter of 10km at 2kpc, it has an angular extent of 10^{-16} radians, a reasonable match to the x-ray resolution.

Of course, we can solve the problem by getting our aspect information from an x-ray interferometer. However, it will take some additional work to determine if this is practical.

D. DIFFRACTION OF BEAM

The x-ray beam itself will diffract as it travels from the primaries to the converger spacecraft. If the beam spreads too far, the signal will be lost, and the sources will become unobservable.

As the baseline B is about one tenth of the distance to the converger, and that mirrors have an effective aperture of d. If the beam must spread to no more than 10d, then we find that the limit is encountered when:

$$\left(\frac{\lambda}{d}\right)10B = 10d$$

using 10cm for d and 1nm for λ we can solve for B. We find that the baselines in excess of about 10,000km will start to have severe losses due to diffraction. However, B rises as the square of d, so if we build unusually large mirrors, or phase smaller mirrors within each spacecraft, we can raise the baseline quickly. Baselines in excess of 1,000,000km become acceptable.

E. BRIGHTNESS OF TARGETS

Figure 1.1 has already addressed this problem. We find that a blackbody with a surface temperature of 10^7K will generate sufficient signal that a resolution of 10^{-15} arcseconds can be recorded. Also shown on the graph is that the baseline needed to achieve this resolution is 10^8km, close to an AU.